

Measurements of $\vec{H}\vec{D}(\vec{\gamma}, \pi)$ and Implications for Convergence of the GDH Integral

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We report new measurements of inclusive π production from frozen-spin HD for polarized photon beams covering the $\Delta(1232)$ resonance. These provide data simultaneously on both H and D with nearly complete angular distributions of the spin-difference cross sections entering the Gerasimov-Drell-Hearn (GDH) sum rule. Recent results from Mainz and Bonn exceed the GDH prediction for the proton by $22 \mu\text{b}$, suggesting as yet unmeasured high-energy components. Our π^0 data reveal a different angular dependence than assumed in Mainz analyses and integrate to a value that is $18 \mu\text{b}$ lower, suggesting a more rapid convergence. Our results for deuterium are somewhat lower than published data, considerably more precise and generally lower than available calculations.

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In 1966 three sets of authors, Gerasimov [1], Drell and Hearn [2] and Hosoda and Yamamoto [3] independently derived a sum rule for the anomalous magnetic moment (κ) of spin $S = 1/2$ particles in terms of the energy-weighted difference between total photon reaction cross sections in entrance channel states with parallel (P) and anti-parallel (A) photon and target spin alignments,

$$\int_{\omega_0}^{\infty} \frac{\sigma_P - \sigma_A}{\omega} d\omega = 4S\pi^2\alpha \left(\frac{\kappa}{m}\right)^2. \quad (1)$$

In recent literature this relation for $S = 1/2$ nucleons has been referred to as the *GDH sum rule*. Hosoda and Yamamoto also showed that the same relation holds for spin $S = 1$ nuclei, such as the deuteron [4]. This expression follows from a Gell-mann–Goldberger–Thirring dispersion relation for the forward elastic (Compton) amplitude [5], provided that the spin-flip Compton amplitude vanishes at high energy at least as fast as $1/\ln(\omega)$. Because of the latter requirement, this sum rule is not fundamental, in that no underlying theory falls if it is violated. Rather, convergence of the above integral to a value different from the right side of eqn. 1 would reveal an interesting property of a very high-energy process.

For the proton and deuteron, the right hand side of eqn. 1 reduces to $204 \mu\text{b}$ and $0.7 \mu\text{b}$, respectively. Recently, a collaboration from Mainz and Bonn has ex-

perimentally checked the GDH sum rule for the proton [6], and at least consistency with calculations for the deuteron over a limited energy range [7]. Their proton measurements spanned the energy range from 0.2 to 2.9 GeV and yielded $254 \pm 5 \pm 12 \mu\text{b}$, exceeding the sum rule expectation. Multipole analyses such as SAID [8] or MAID [9] agree that a contribution of $-28 \mu\text{b}$ is expected from the near threshold region below 0.2 GeV. This would require an as yet unmeasured $-22 \mu\text{b}$ from high energies to restore agreement with the expectations of eqn. 1, which is possible since some negative contributions have been suggested by Regge models [10, 11].

We report here new measurements of inclusive π photo-production from a polarized HD target, spanning a range of polarized photon energies covering the $P_{33} \Delta$ resonance. The experiments were performed at the Laser Electron Gamma Source (LEGS) at Brookhaven National Laboratory with tagged circular polarized γ -rays between 190 and 420 MeV. The general characteristics of the LEGS photon beams are discussed in ref [12]. Here the photon polarization averaged between 60% to 99% and was cycled between left and right circular states at randomly chosen times averaging every few minutes.

The polarized target consisted of solid hydrogen-deuteride (HD), held in a frozen-spin state. The material was condensed in a variable temperature cryostat, where

the NMR polarization monitoring system was calibrated at 2 K, transferred to a dilution refrigerator for polarization at ~ 15 mK and 15 Tesla, held there for typically 3 months to reach the frozen-spin state, and finally transferred to an In-Beam Cryostat (IBC) operating at 0.3 K, where a thin 0.9 Tesla solenoid maintained the H and D orientations. The polarization cycle will be detailed in a separate publication. Some aspects are discussed in [13]. Data were collected during two running periods in Fall 2004 and Spring 2005, the first emphasizing H polarization, with initial polarizations of $P(H) = 0.59$ and $P(D) = 0.07$, and the second using increased D polarization following an RF transfer of spin between H and D, with $P(H) = 0.32$ and $P(D) = 0.33$. Mid-way through each period the H polarization was flipped with an RF transition. This produced four distinct data blocks with differing target polarizations, during which the in-beam spin relaxation times for polarized H and D ranged from 7 to 15 months. The polarization was monitored frequently with a cross-coil NMR system within the IBC [14].

For these measurements, pions were detected in a large *Spin Asymmetry* (SASY) calorimeter. An array of 432 NaI(Tl) detectors, an XBOX, surrounded the target covering laboratory (Lab) angles from 45° to 135° . A cylindrical array of plastic neutron detectors was positioned between the XBOX and the IBC. (Results for exclusive channels will be discussed elsewhere.) A forward wall consisting of 31 cm of plastic scintillators, backed by an array of 176 Pb-Glass crystals detected reaction products at Lab angles between 10° and 40° . The configuration of these detectors was optimized for neutral pions, with either two decay photons detected in the XBOX or one in the XBOX and the other in the forward wall. This provided nearly complete coverage for π^0 detection.

Two-pion production is negligible throughout our energy range [15]. As a result, spectra at a fixed angle and tagged energy are dominated by 2-body (from H) or quasi-2-body (from D) kinematics. The energy of reconstructed neutral pions is compared to the 2-body expectation in Fig. 1 for one of 10 angle bins, 17 tagged energy bins and 4 target polarization groups. The simulated response (blue curve) is in excellent agreement. The spin asymmetry is evident in the left and right panels, which show yields for parallel and anti-parallel beam and target spin alignments. Charged pion spectra are very similar.

The only unpolarizable nucleons in the target are found in a mesh of $50 \mu\text{m}$ Al wires used to conduct away heat during polarization and in pCTFE (C_2ClF_3) windows of the target cell. Their contributions are determined through empty cell measurements (black area in Fig. 1).

We discuss here inclusive π production, integrated over azimuthal angles, for which the differential cross section from polarized HD can be written as [13, 16],

$$d\sigma(\theta, E_\gamma) = d\sigma_0^{HD} - P_\gamma^c P_H \hat{E}_H - P_\gamma^c P_D^V \hat{E}_D + \sqrt{1/2} P_D^T \hat{T}_{20}^0, \quad (2)$$

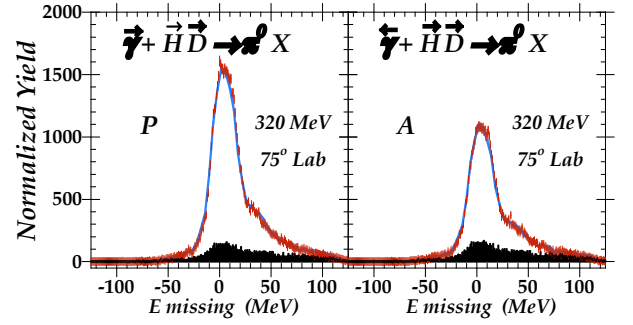


FIG. 1: Differences between 2-body kinematics and the measured π^0 energy are shown in red, for parallel (left) and anti-parallel (right) beam and target spin alignments. Simulated energy differences are shown as the solid (blue) curves. Empty cell contributions are shaded in black.

where P_γ^c is the circular beam polarization, P_H is the hydrogen polarization, P_D^V and P_D^T are the deuteron vector and tensor polarizations, respectively, and a subscript zero (0) denotes an unpolarized cross section. Here we have designated the numerator of a spin asymmetry with a caret, so that $\hat{E}_H = d\sigma_0^H E_H = 1/2 [d\sigma^H(A) - d\sigma^H(P)]$, \hat{E}_D is the corresponding quantity for deuterium and $\sqrt{1/2} \hat{T}_{20}^0 = \sqrt{1/2} d\sigma_0^D T_{20}^0 = 1/2 [d\sigma^D(A) + d\sigma^D(P) - 2d\sigma_0^D]$ is the deuteron tensor observable, following the convention of [16].

The data set consists of four distinct blocks with different target polarizations, each containing roughly equal amounts of data with right and left circular photon polarization. These eight data groups overdetermine the four observables of eqn. 2. Fits varying \hat{T}_{20}^0 produced at most few percent changes in $d\sigma_0^{HD}$, compared to fixing \hat{T}_{20}^0 to zero, and no perceptible changes to \hat{E}_H and \hat{E}_D . Here we focus on results of fits with \hat{T}_{20}^0 fixed to zero.

Sample angular distributions of the unpolarized cross section at the peak of the $\Delta(1232)$ are shown in Fig. 2 (solid circles). To compare with other available deuteron data we have subtracted the well-known proton cross sections as parameterized by SAID(FA07k) [8]. Here we show results for the Fall'04 data for which the deuteron tensor polarization was negligible.

The normalization scale was checked by comparing $D(\gamma, \pi^0)X$ cross sections to data collected with the same detector array using a liquid D_2 target of known length (open circles in Fig. 2). The Fall'04 target was grown slowly and its length agreed with that expected from the known amount of HD gas. The Spring'05 target was grown rapidly and its cross section scale was normalized to the Fall'04 $D(\gamma, \pi^0)X$ by fitting to the interval $110^\circ \leq \theta_{Lab}^\pi \leq 150^\circ$ where both our fits and the calculations of [16] agree that \hat{T}_{20}^0 is negligible.

Differential spin-difference cross sections, $[d\sigma^H(P) - d\sigma^H(A)] = -2\hat{E}_H$, for polarized H are shown in Fig. 3 as solid circles for energies near the peak of the Δ . Since

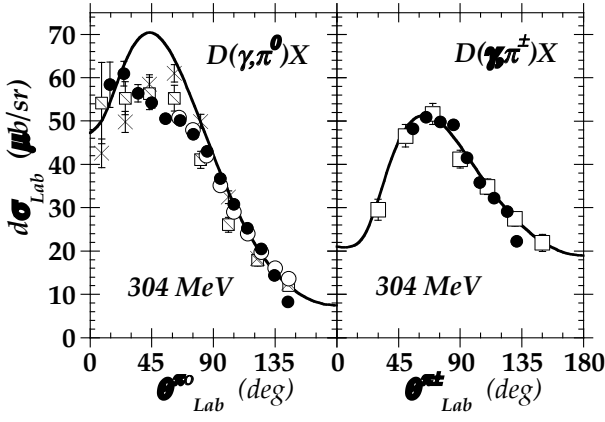


FIG. 2: Unpolarized cross sections (solid circles) for $D(\gamma, \pi^0)X$, left, and $D(\gamma, \pi^\pm)X$, right, at $E_\gamma = 304$ MeV, deduced by subtracting SAID(FA07k) predictions [8] for $p(\gamma, \pi)$ from fitted HD results. For the π^0 channel, LEGS data from a liquid D_2 target are shown as open circles, while crosses and hatched-boxes are from [17] and [15]. For the π^\pm channel, open boxes are constructed from π^-pp [18] and the π^-/π^+ ratio data of [19]. The curves are calculations from [16].

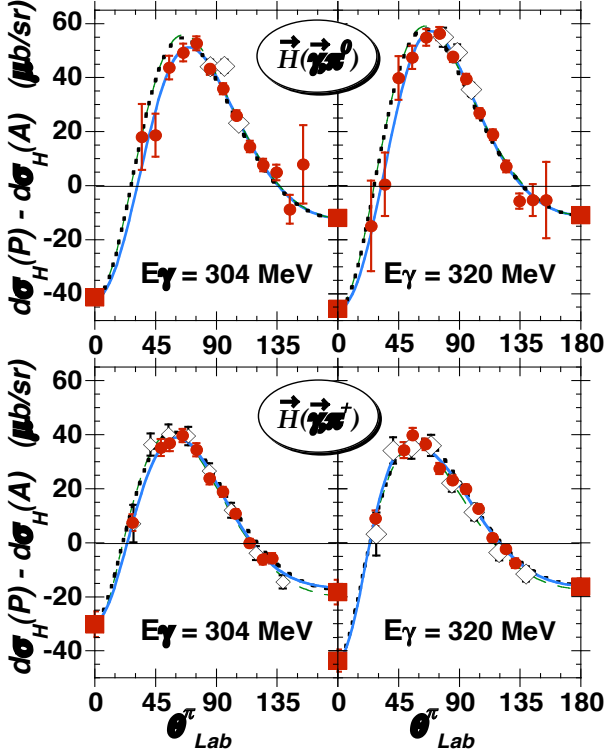


FIG. 3: Angular dependence of the $[P - A]$ spin-difference cross section for polarized H at beam energies near the Δ peak. The full data are solid (red) circles. Unpolarized limits (solid red squares) at 0° and 180° are the means of SAID [8] and MAID [9]. Open diamonds are from Mainz [20], interpolated to these energies. Predictions from SAID and MAID are dotted (black) and dashed (green) curves, respectively. Solid (blue) lines show Legendre fits to our data.

the pion has zero spin, at 0° and 180° the H spin difference reduces to $-2d\sigma_0^H$. For these angles, the mean of SAID(FA07k) [8] and MAID(2007) [9] were used (solid squares). The Mainz H-Butanol results for π^+ are in very good agreement with the present data, both here and at other energies. SAID and MAID multipole predictions, which include the Mainz data in their fits, reproduce the angular dependence of the π^+ spin difference. The Mainz π^0 differential spin difference data are again in good agreement with our results, although they have a very limited angular range [20]. However, forward of 80° in the laboratory, our spin-difference results drop below the multipole prediction of SAID and MAID. This trend occurs mainly near the Δ peak. At energies 40 MeV higher or lower, SAID and MAID π^0 predictions are quite close to our data.

The angular distributions of the π spin-difference cross sections have been fitted to a Legendre expansion (solid blue curves in Fig. 3). The integration of these distributions are shown as the open (red) crosses in Fig. 4. Our total spin difference for π^+ from polarized H (Fig. 4, top) is in excellent agreement with Mainz results [20], although limited to energies above 270 MeV by absorption in the neutron detectors surrounding the HD target. The π^0 spin-difference is lower than the Mainz results in the region of the Δ peak (Fig. 4, second panel from top), reflecting the differences in the angular distributions

Another method of obtaining total cross sections is to simply count pions in the full detector. This technique was used in Mainz experiments. All quasi- 4π detectors have efficiencies that vary with angle, which must be corrected using simulations. However, it is important to use accurate angular distributions to distribute events in such simulations to avoid biasing results, particularly when cross sections vary rapidly with angle. Counting neutral pions in the SASY detector, with efficiencies corrected by simulation using measured angular distributions, results in the solid (red) circles of Fig. 4. This agrees with direct integration of the angular distributions, and has smaller uncertainties since it avoids propagating errors from multiple background subtractions.

Systematic uncertainties on the cross section scale associated with target length, flux normalizations and possible geometrical differences between the detector and the simulations are estimated at 3.5%. Photon beam polarizations are known to 1%. Systematic uncertainties on target polarization vary between data groups. Their effect produces a 5.1% uncertainty in the integrated spin-difference. The total systematic uncertainty in GDH(p) is then 6.3%.

The π^0 contribution to the running GDH integral for the proton is plotted against the upper limit of integration in Fig. 4 (third panel from top). From 200 MeV to 420 MeV, our integrated result is $125.4 \pm 1.7 \mu b$. Integration of the Mainz data over the same interval gives $142.9 \pm 5.4 \mu b$ [20]. This difference of $-17.5 \pm 5.7 \mu b$

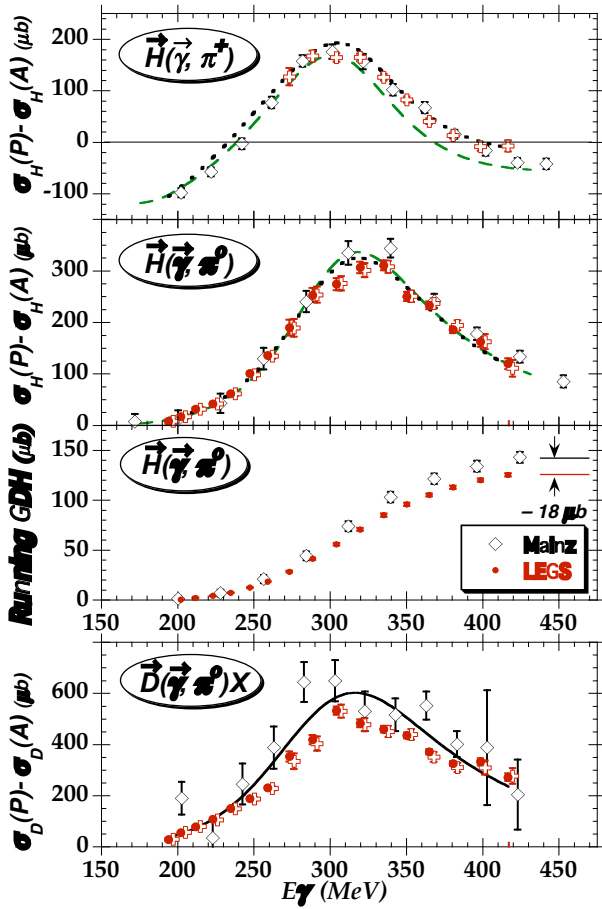


FIG. 4: Total π^+ and π^0 spin-difference cross sections for polarized H (top two panels) and for π^0 production from polarized D (bottom). Open (red) crosses result from an angle integration of the differential spin difference (π^0 crosses are shifted by +3 MeV for clarity). Solid (red) circles result from counting π 's in the detector, using the measured angular dependences in a simulation to correct for varying efficiencies. Mainz results, using the latter method, are shown as open diamonds [7, 20]. The π^0 contribution to the running GDH(p) is plotted in the second to bottom panel against the upper limit of integration. Curves are as in Fig. 2 and Fig. 3.

appears to originate from a limited energy range. Applying this correction to the full Mainz+Bonn result, together with the $-28 \mu\text{b}$ contribution from energies below 0.2 GeV, would bring their GDH(p) total down to $208 \pm 6 \text{ (stat)} \pm 14 \text{ (sys)} \mu\text{b}$, where we have combined here the systematic uncertainties from both experiments. This is to be compared with $204 \mu\text{b}$ for the right side of eqn. 1 and removes the need for additional canceling contributions from higher energies to achieve agreement with the GDH(p).

The integrated spin difference for π^0 production from the deuteron is shown in the bottom panel of Fig. 4. These are somewhat lower than the Mainz results of [7] and considerably more precise. The calculation of [16] is shown as the solid curve. While certainly in proximity to the data, further theoretical work will be needed

to address the discrepancies which are largest in the π^0 channel (Fig. 2 as well).

In summary, while our charged- π data from polarized H agree with Mainz, our π^0 results near the peak of the Δ reveal a different angular distribution than what was assumed in Mainz analyses. As a result, our π^0 contribution to eqn. 1 is $18 \mu\text{b}$ less than the Mainz result for H and suggests that a high-energy Regge tail is not needed. Our results for polarized D are lower than the trend of the Mainz data and have considerably smaller uncertainties. The data are also lower than recent deuteron calculations and point to the need for additional theoretical work to understand the GDH(D) convergence.

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